Application Note **AN-9001**

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IGBT4 and free wheeling diode CAL4 in IGBT modules

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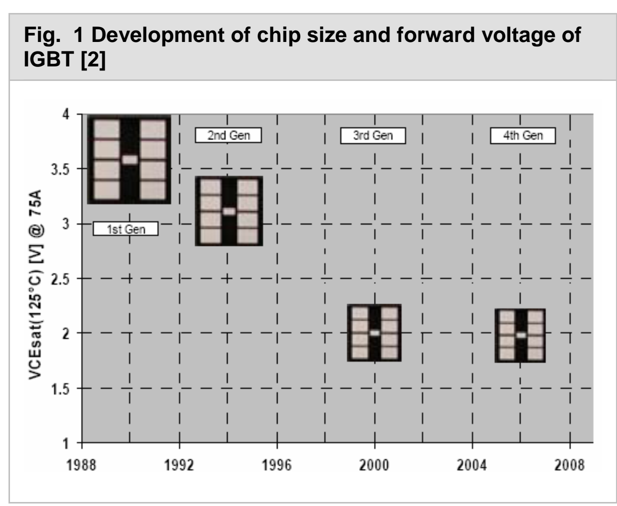
SEMIKRON's IGBT modules are set to feature the new IGBT4 chip from Infineon as well as the well adapted CAL4 free-wheeling diode from SEMIKRON. The new devices will end with the extension "12T4" or "12E4" depending on the used chip setting. They will gradually replace previous IGBT generations.

This application note replaces AN-7005.

General properties

Power module users expect a new IGBT generation to bring about lower losses and higher nominal currents per volume. Ongoing developments in the area of chip size reduction can be seen in figure 1. With the 4th generation of Trench Field Stop IGBT's the current density could be increased from 85 A/cm² (SPT) or 115 A/cm² (IGBT3) to 130 A/cm² (IGBT4). Chip size was optimized to bring about a better trade-off between cost and performance. In general, the chip size reduction allows for higher power density in power modules with the drawback of higher thermal resistances.
To compensate this, a higher power density should go hand in hand with reduced power dissipation. Where, in the development stage from 2nd to 3rd generation, the focus was on reducing forward voltage (conducting losses), this time the main aim was to achieve lower switching losses and softer switching behaviour.
A further improvement could be achieved with the 25°C higher maximum junction temperature. The power semiconductors now have a maximum junction temperature of $T_{j(max)}$ =175°C. With a safety margin of 25°C, it is now possible to operate up to T_j = 150 °C and to achieve approx. 20% higher inverter output power from devices with the same nominal current. Alternatively, a device with a lower rated current may be used for the same inverter power (see cross reference list at the end of the document).

Fig. 1 Development of chip size and forward voltage of IGBT [2]



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The following table provides an overview of the main parameters responsible for device losses and temperatures. For better comparison, the values for all devices are given for T_j = 125°C and the data sheet values for IGBT4 at 150°C are added in brackets.

Table 1: Parameter comparison for 1200V/100A nominal chip current

	SPT (…128)	IGBT3 (…126)	IGBT4 (…12T4) [150°C]	IGBT4 (…12E4) [150°C]
$V_{CE(sat)}$ 25°C	1.9 V	1.7 V	1.8 V	1.8 V
$V_{CE(sat)}$ 125°C	2.1 V	2.0 V	2.1 V [2,2 V]	2.1 V [2,2 V]
E_{sw} 125°C	22 mJ	27mJ	19mJ [21mJ]	22mJ [24mJ]
$R_{th(j-c)}$	0.17 K/W	0.24 K/W	0.27 K/W	0.27 K/W
Q_G (V_{GE}=-8V/-15V)	1.2µC	0.9µC	0.57µC	0.57µC
$T_{j(max)}$	150°C	150°C	175°C	175°C

Chip selection

For the new IGBT4 two different chip settings are available. Minimum switching losses yet with maximum di/dt are achieved with the fast "T4" chip. Fast switching goes hand in hand with high transients in current and voltage. As a consequence, high overvoltages at high currents are induced by parasitic stray inductances. This chip will therefore be the preferred choice for devices with lower nominal current up to 150A or for applications with a low DC-Link voltage in the 600V range.
Low switching losses but softer turn-off can be achieved with the "E4" chip. As a result, this chip is more suitable for applications with high currents, applications with modules connected in parallel or higher DC-Link voltages.

Table 2: Available chip sets in SEMIKRON IGBT modules

SEMITOP ®	T4
MiniSKiiP ®	T4
SEMITRANS 2 ®	T4
SEMITRANS 3 and 4®	T4/E4
SEMiX ®	E4
SKiM63/93 ®	E4
SKiiP ®	E4

Switching behaviour

The IGBT4 has far lower switching losses than the IGBT3 and slightly lower or comparable values than for the SPT IGBT. The turn-off losses could be reduced by around 30%. This means that applications with higher switching frequencies (> 4 kHz) can benefit in particular from these new IGBT modules. The data sheet values are now given for T_j=150°C owing to the higher operating junction temperature.
At 125°C the switching losses are lower. To compare the values for this temperature with other data sheet statements given for 125°C, the IGBT switching losses are to be multiplied by a factor of 0.91. The switching losses as a function of the junction temperature can be calculated using a linear temperature coefficient with the formula:

$$E_{sw}(T_j) = E_{sw}(150°C) \cdot \left(1 - TC \cdot \left(150°C - T_j\right)\right)$$

where TC_I = 0.0033 for the IGBT and TC_D = 0.006 for the free-wheeling diode. Figure 2 shows the measured values as well as the adaptation using the formula above.

Fig. 2 Switching losses as a function of junction temperature for a 200A IGBT and diode

For Trench IGBTs the switching behaviour at turn-off is different than that of SPT or previous Non Punch Through IGBTs (NPT: 123, 124 125 series). As known from Trench 3 IGBTs, the gate resistor $R_{G(off)}$ has only a limited influenced on the turn-off behaviour. This applies in particular to the "T4" chip, which is shown on the example of a 150A MiniSKiiP in Fig. 3 to 6. Turn-off losses E_{off} are constant over a wide range. Sometimes the fall time t_f even decreases with an increasing gate resistor. The I_C and V_{CE} waveform are almost identical.
For the "E4" chip, a decrease in switching speed occurs when the gate resistor increases. For this reason, it is more suitable for high power applications with currents of several 100A. This makes it easier to stay within the reverse bias safe operating area RBSOA with the turn-off overvoltage spike (**Fig. 7**). An increased gate resistor

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allows to turn-off the current in the whole range from nominal current to short circuit. In this case, different values for $R_{G(on)}$ and $R_{G(off)}$ should be used to achieve low turn-on losses and manage the overvoltage at turn-off.

The slower switching of the E4 chip increases the switching losses by about 15% (**Fig. 8**). Typical values for E_{sw} are given in Table 1. Data sheet values vary depending on the package type.

Fig. 3 Switching losses of a 150A T4 IGBT module as a function of gate resistor

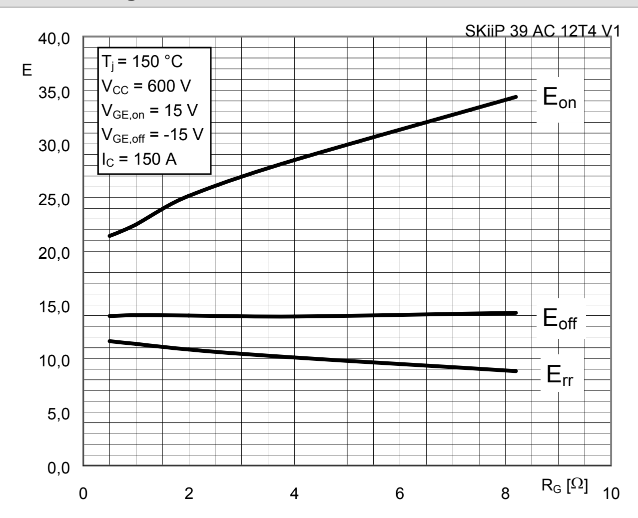


Fig. 4 Switching times of a 150A T4 IGBT module as a function of gate resistor

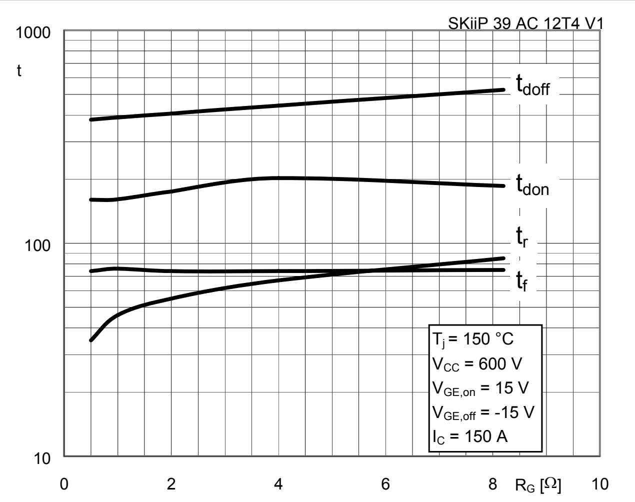


Fig. 5 Turn-on behaviour of a 150A T4 IGBT at different gate resistors (Green: V_{CE}, Red: I_C; — R_g=0,5Ω, - - R_g=8Ω)

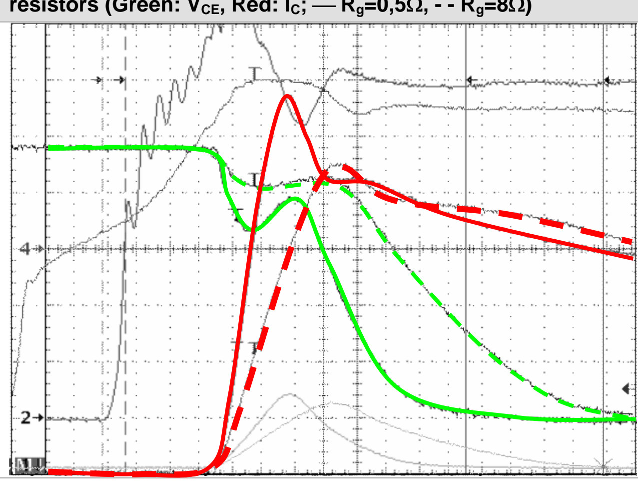


Fig. 6 Turn-off behaviour of a 150A T4 IGBT at different gate resistors (Green: V_{CE}, Red: I_C; — R_g=0,5Ω, - - R_g=8Ω)

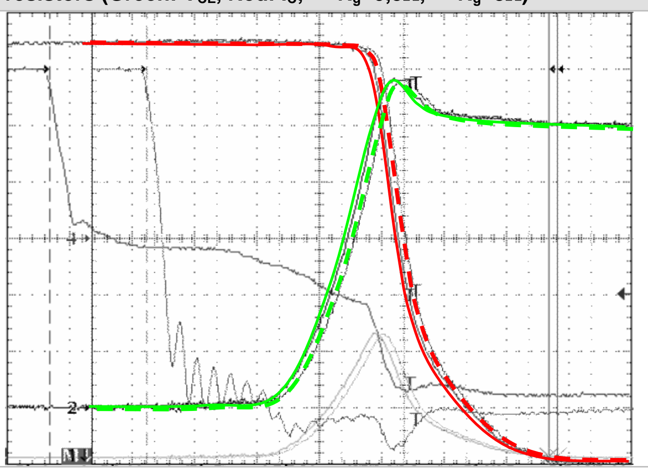


Fig. 7 Overvoltage at turn-off of a 450A module at T_j=25°C, V_{CC}=800V as a function of collector current

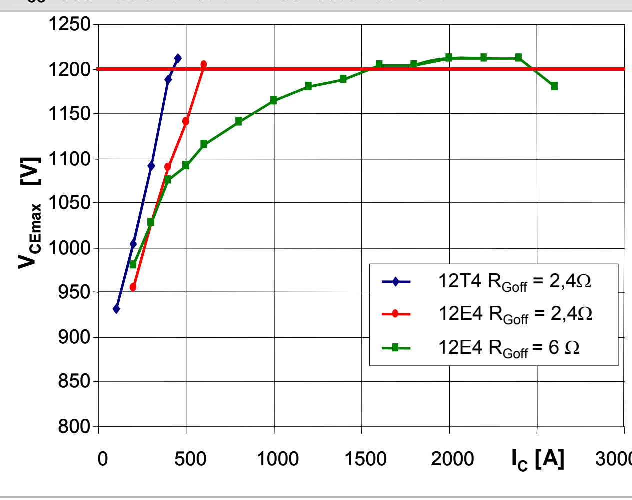
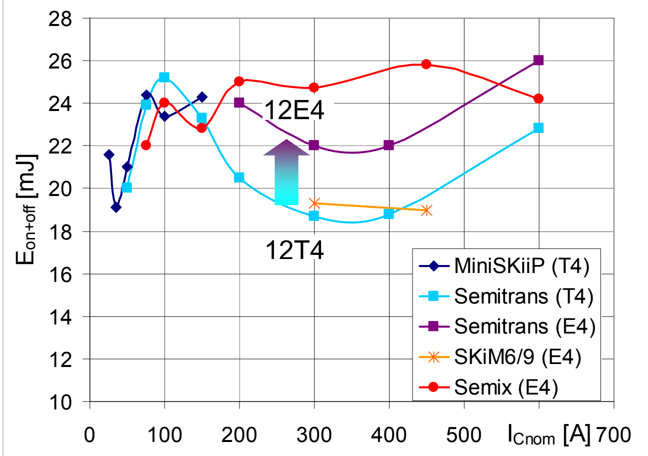


Fig. 8 Comparison of switching losses per 100A nominal current for different cases and chips settings



Overvoltages

At turn-off, the di/dt of the collector current causes a voltage spike dV_{CE} across the parasitic inductances, which is added to the DC link voltage. At nominal device current this is normally within the gap between DC-link voltage and device blocking voltage. It can become a serious problem, when turning-off over current or short-circuit currents of several 100A and more.
Care must be taken to ensure that the maximum blocking voltage of the devices is not exceeded at chip level (see AN-7006 for details on peak voltage measurement). The internal voltage drop caused by the parasitic module inductances L_{CE} has to be added to the voltage measured at the main terminals. Depending on the module design and the di/dt, this can be around 100V. Measurements taken at auxiliary contacts (Ex, Cx) show the voltage close to chip level.

The overvoltage dV_{CE} will increase in the following cases:

- for lower temperatures (**Fig. 9**) at $R_{G(nom)}$ but has its maximum at different R_G cold and hot
- additionally to a higher DC-Link voltage (**Fig. 10**)
- with higher currents
- if the faster IGBT "12T4" is used (**Fig. 11**)
- for short turn-on times <5µs (**Fig. 12**)

Contrary to expectations, both the di/dt and the turn-off voltage spike can increases with increasing gate resistance. A substantial reduction in the overvoltage can be achieved for the "12T4" chip with very high gate resistances $R_{G(off)}$ only (e.g. >20Ω for a 300A module). Under normal operating conditions, this would result in high turn-off losses. But it can be used to turn off the IGBT at overcurrents > 2* $I_{C(nom)}$ as a soft turn-off.
For high-power applications with several 100A which operate at DC-link voltage levels >700V, the use of a snubber capacitor between +/- DC is recommended.

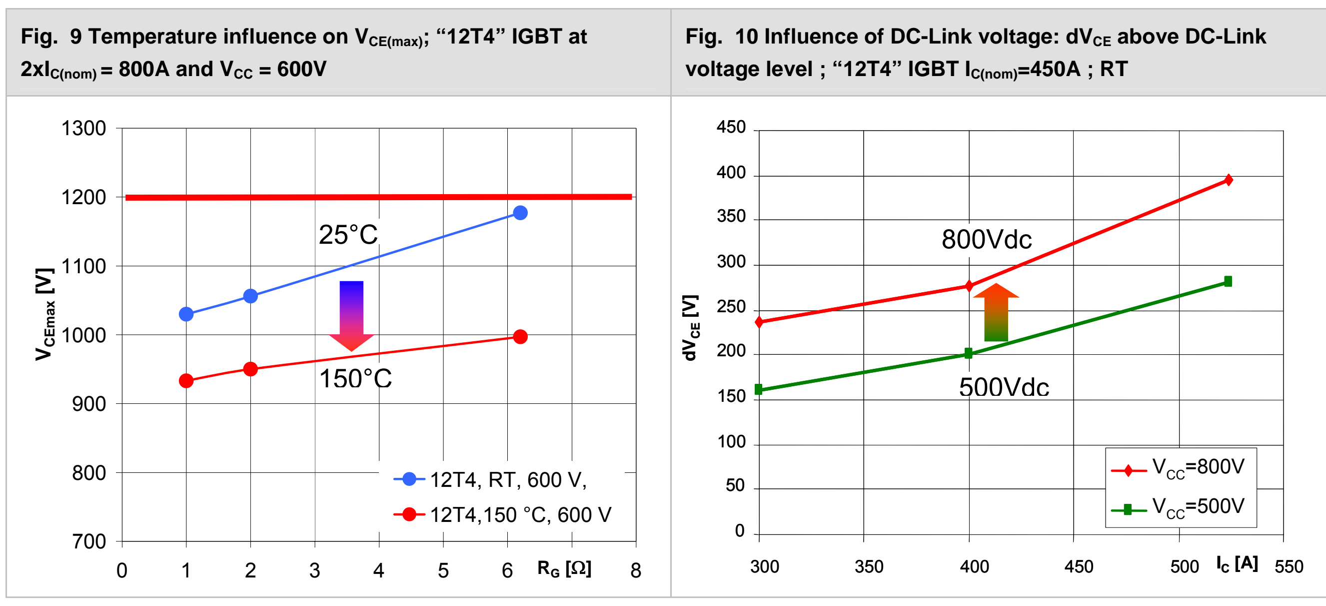


Fig. 9 Temperature influence on $V_{CE(max)}$; "12T4" IGBT at $2xI_{C(nom)}$ = 800A and V_{CC} = 600V

Fig. 10 Influence of DC-Link voltage: dV_{CE} above DC-Link voltage level ; "12T4" IGBT $I_{C(nom)}$=450A ; RT

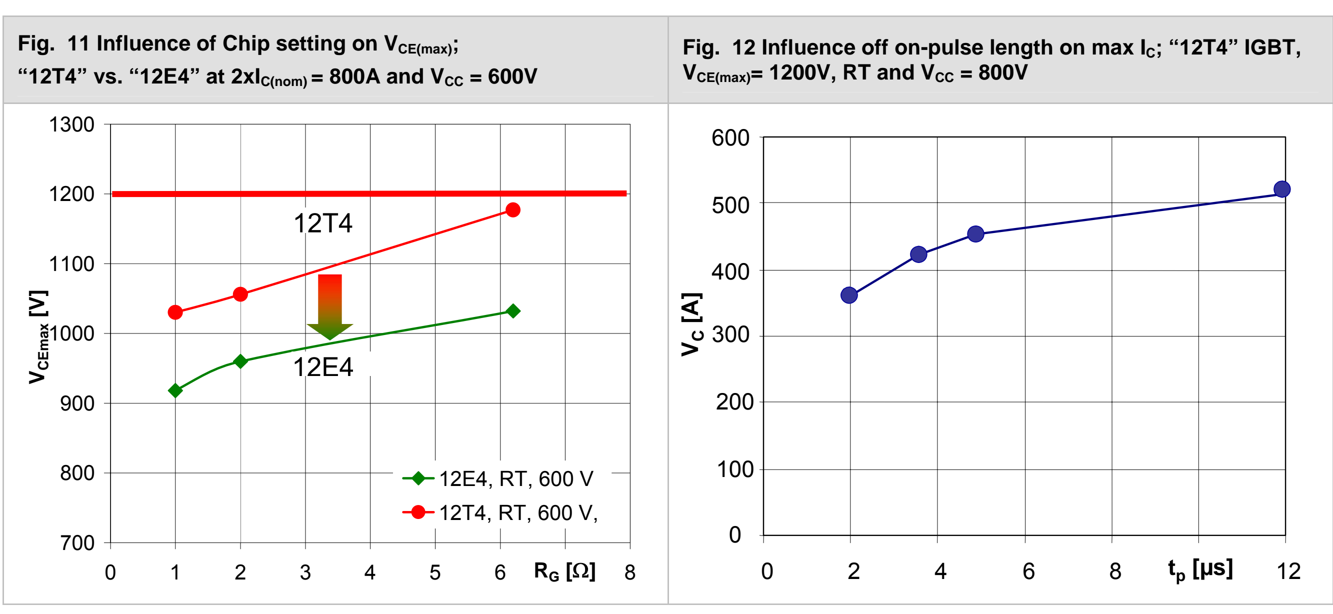


Fig. 11 Influence of Chip setting on $V_{CE(max)}$; "12T4" vs. "12E4" at $2xI_{C(nom)}$ = 800A and V_{CC} = 600V

Fig. 12 Influence off on-pulse length on max I_C; "12T4" IGBT, $V_{CE(max)}$= 1200V, RT and V_{CC} = 800V

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Short-circuit turn-off

The energy during short circuit conditions is limited to the following boundary conditions:

- a maximum duration of 10µs,
- temperatures up to T_j=150°C and
- a maximum DC-Link voltage of 800V

A “short-circuit 2” – with low external inductance between IGBT and DC potential – is shown in **Fig. 13**, and a hard short-circuit (“SC 1”) where both IGBTs of a bridge leg are turned on simultaneously in **Fig. 14**.

In the final application, it has to be checked if a turn-off with the nominal R_G is possible. This can be at low DC-Link voltage (e.g. V_{CC} = 600V) or if an existing overcurrent protection can react fast enough before desaturation occurs (e.g. I_{trip} <= 2x $I_{C(nom)}$). The current rise in the case of “SC2” depends on the minimum external short circuit inductance and the DC-Link voltage. The rise time of a short circuit current until desaturation can be calculated roughly using the following equation:

$$t_{r(SC)} = \frac{L_{SC(min)} \cdot 3 \cdot I_{C(nom)}}{V_{CC(max)}}$$

The overcurrent protection has to turn off the IGBT before this point is reached.

Soft turn-off is necessary for a higher DC link voltage or if the short circuit turn-off was triggered by $V_{CE(sat)}$ monitoring of an IGBT in desaturation. Soft turn-off can be realised using a second turn-off transistor in the driver output stage with an increased $R_{G(off)SC}$ or an intermediate step at a reduced turn-off voltage (e.g. $V_{GE(off)}$ = 0V) for a short time. An exact value for the soft turn-off resistor can only be specified in the final application, because the overvoltage is caused by the parasitic inductances in the circuit, which is very likely to be different from the measurement circuit used for the following figures. In that example, the 450A SEMiX module had to be switched off with $R_{G(off)SC}$ = 15Ω at V_{CC}=800V but has a nominal “data sheet” R_{Goff} = 2Ω.

Furthermore, for high-power applications gate voltage clamping is recommended to limit the gate voltage to slightly above 15V. The fast rising current and the Miller effect in case of desaturation can increase the gate voltage and lead to much higher short circuit currents.

The clamping can be achieved using Zener diodes between gate-emitter terminals or with a Schottky diode between the gate terminal and the +15V power supply. Both measures have to be as close as possible to the device terminals. The inductance of long connections or the external gate resistance would make the clamping ineffective.

Fig. 13 Short-circuit, one IGBT turned on via a short cable (T_j=150°C, V_{CC}=800V, $V_{CE(max)}$ =1038V, I_{CM}=2360A (5,2x$I_{C(nom)}$), $R_{G(off)}$ = 15 Ω)

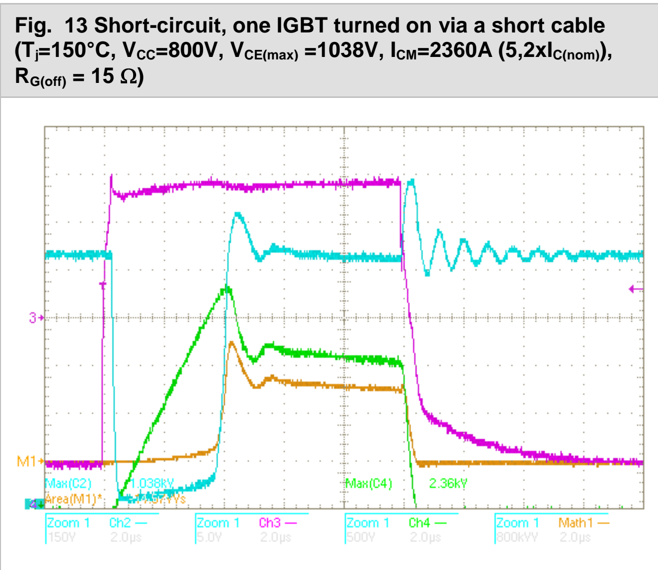
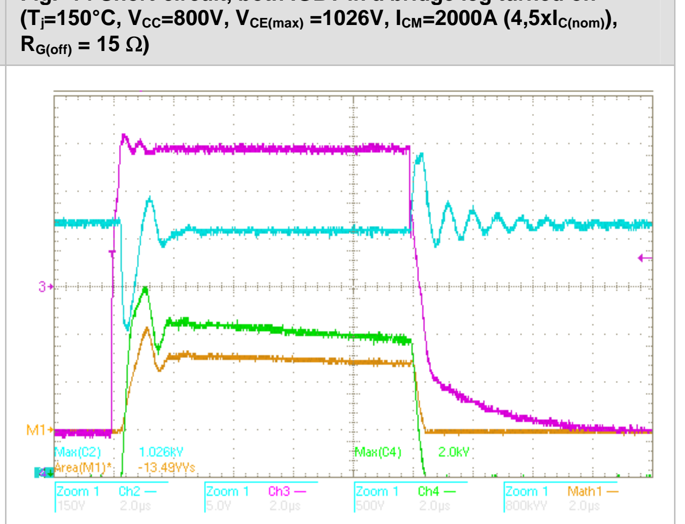


Fig. 14 Short-circuit, both IGBT in a bridge leg turned on (T_j=150°C, V_{CC}=800V, $V_{CE(max)}$ =1026V, I_{CM}=2000A (4,5x$I_{C(nom)}$), $R_{G(off)}$ = 15 Ω)

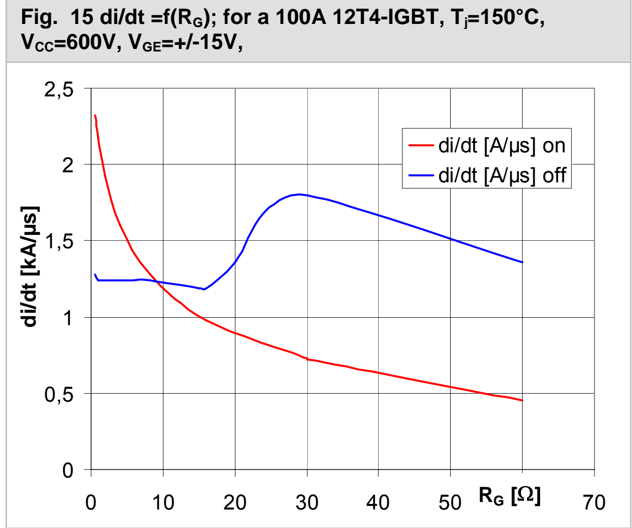


EMI considerations

The EMI spectrum of an inverter is influenced mainly by the voltage $V_{CE}(t)$ and current $I_C(t)$ gradients of the switching power semiconductors. To benefit from the lower switching losses the device has to be switched very fast. Typical values for a 100A-IGBT can be seen in **Fig. 15**. At high temperatures the devices switches softer and the gradients are about 50…60% of the cold values. The di/dt increases almost linear to the current at turn-off and only slightly with the DC-link voltage.

The di/dt and dv/dt during turn-on can be set by the chosen R_G. There is an almost linear relationship between gate resistor, voltage and current gradients, on the one hand, and switching losses, on the other hand. Unlike what one might expect, di/dt and dv/dt does not decrease with increased R_G at turn-off (**Fig. 5**/**Fig. 6**). In fact, increasing the gate resistance can also increase the di/dt at turn-off, as shown on the example of a 100A MiniSKiiP with a 12T4 chip in **Fig. 15**. The nominal gate resistor for this device is 1Ω. Only for very high gate resistors will the current slope decrease again. This effect is caused by the stored charge carriers at the moment of turn-off. For a low R_G value electrons can still be found in the base region and the high overall charge is responsible for the more moderate current slope. For a medium R_G value the MOS channel of the IGBT is already closed when the current starts to decrease. No electrons contribute to the current flow any more. Only the small number of holes has to be removed, which leads to a high di/dt. A detailed description is given in [3].

Fig. 15 di/dt =f(R_G); for a 100A 12T4-IGBT, T_j=150°C, V_{CC}=600V, V_{GE}=+/-15V,



Internal gate resistor $R_{G(int)}$

To improve the synchronous switching of chips connected in parallel within one module, the larger chips have an integrated gate resistor.

75A chip	10 Ω
100A chip	7.5 Ω
150A chip:	5 Ω
300A = 2 x 150A chip ||:	5Ω/2 =2.5 Ω
400A = 4 x 100A chip ||:	7.5Ω/4 = 1.87 Ω

The gate resistor is not part of the data sheet measurement conditions for switching losses or times. The values given in the data sheets refer to the external gate resistor only. The integrated gate resistor should be considered only with regard to driver circuit dimensioning (maximum gate current I_{GM} or minimum gate resistor $R_{G(min)}$).

Free-wheeling diode

With the introduction of the new CAL-4 diodes, the internal free-wheeling diode has been adapted to the new IGBT. The turn-on losses of the IGBT are influenced by the recovery charge of the diode in applications with inductive load. To benefit from the low IGBT switching losses the diode was also designed for low switching losses and softness even in harsh switching conditions.
Furthermore, the maximum junction temperature of the diode matches the IGBT. Both semiconductors have a maximum value of $T_{j(max)}$=175°C. The new CAL4 diode provides about 30% more power with the same chip size. [4]

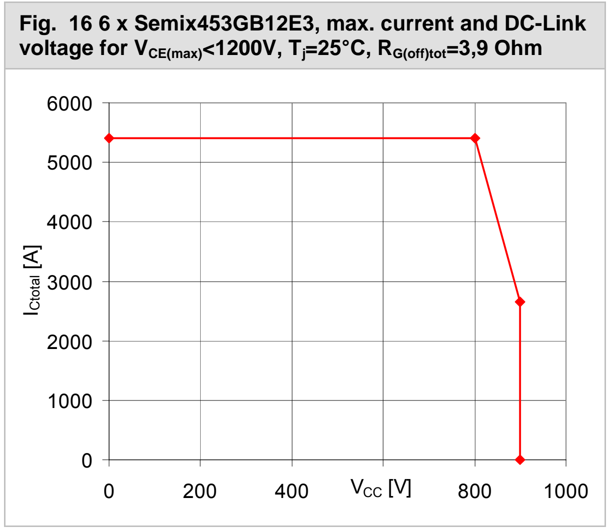
Driver circuit adaptation

In existing applications a 1:1 replacement is not feasible. At the very least, the gate resistor should be adapted to the new device. If, for example, an SPT-IGBT SKM200GB128D were to be replaced by a SKM150GB12T4G, the nominal R_G, which was 7Ω for the SPT, would be 1Ω for the IGBT4. Keeping the old R_G together with the new IGBT would result in higher switching losses (E_{on}(1Ω) = 19mJ → E_{on}(7Ω) = 38mJ) and in tendency also higher voltages at turn-off (see **Fig. 9**). Levels for short-circuit protection with $V_{ce(sat)}$ monitoring can remain but the statements made under "Short circuit turn-off" should also be considered. The power supply is not loaded to the same extent because the gate charge is reduced by more than 30%.
The use of an external gate-emitter capacitor might help to reduce the radiated and conducted noise and prevent unmotivated turn-on caused by dv/dt of other switching devices. It does not reduce the turn-off overvoltage.

Parallel connection

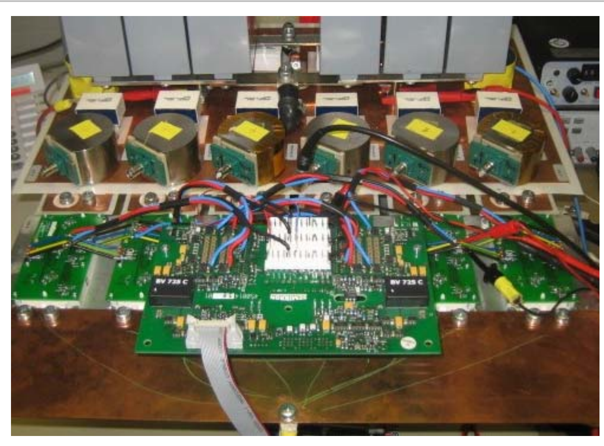
Parallel connection of IGBT modules is used for high inverter output currents. Due to the high currents and the mechanical dimensions, turn-off overvoltages are always a critical point in such applications. The slower 12E4 chip is the preferred device, because of its better controllability at turn-off. With a test setup of 6 x 450A Semix453GB12E4 it was proven that devices are able to operate at a maximum DC-Link voltage of 800V and turn-off currents of 2x $I_{C(nom)}$ = 5400A without any problems.

Fig. 16 6 x Semix453GB12E3, max. current and DC-Link voltage for $V_{CE(max)}$<1200V, T_j=25°C, $R_{G(off)tot}$=3,9 Ohm



As for any other IGBT, a low inductive symmetrical DC-link design is necessary. Snubber capacitors should be used at each device DC terminal. Each module needs its own adapter board with individual gate and auxiliary emitter resistors per switch. The wire connections between the Gate driver and the adapter boards are twisted and have the same length for all modules.

Fig. 17 Test assembly with 6 x SEMiX453GB12E4, individual adapter board, driver and AC terminal in front



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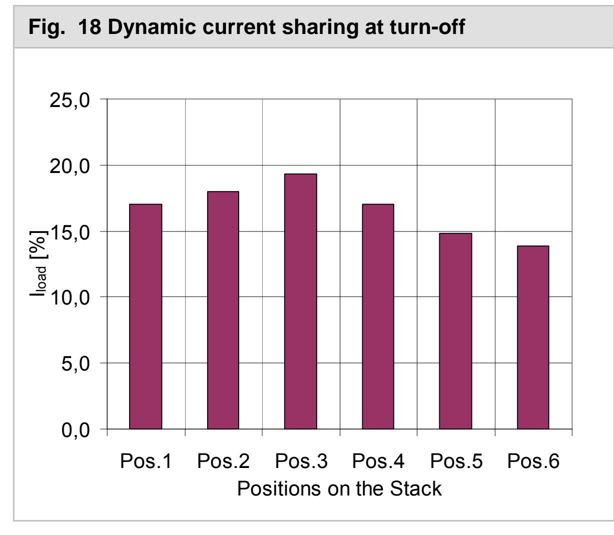
For parallel connection, derating of the maximum inverter current of about 10% should be taken into consideration. The reason for this is non-homogenous current sharing, which depends mainly on the common AC connection point of the 6 modules. The device closest to the connection point in the middle position with the lowest impedance in the parallel connection has the highest current at turn-off. This effect is superimposed by the semiconductor properties. Dynamic current sharing is shown in **Fig. 18** and is between 19 and 13.6% of the total current, where the average is 16.6%. The values differ slightly for Top and Bottom IGBT in the half bridge. At turn-on the currents are almost balanced out.

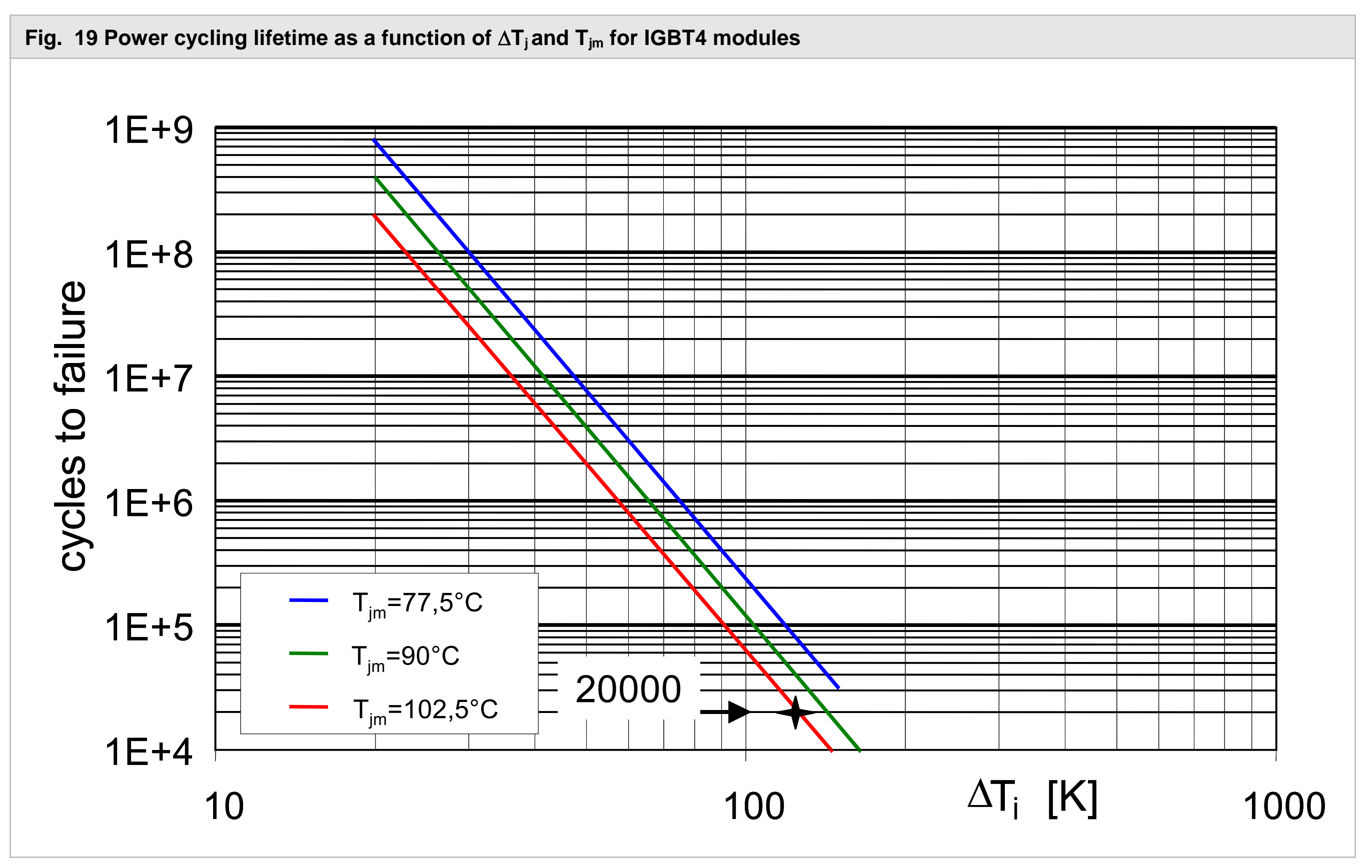
Fig. 18 Dynamic current sharing at turn-off



Power cycling

IGBT modules with IGBT 4 / CAL4 can be operated at up to 150°C (max. junction temperature at 175°C). By optimizing the wire bonding and device design engineering, a 25K higher junction temperature swing can now be achieved without reducing the projected device lifetime. The expected lifetime is now 20,000 cycles with dT=125K. For this reason, a new cross reference list (see below) based on the new reliability test data was established. To predict the lifetime of power modules in applications, accelerated lifetime tests are performed. These tests are carried out with high temperature swings (e.g. ΔT_j =100K and ΔT_j =125K) to shorten the test time to failure. Lifetime predictions for lower temperature swings (e.g. ΔT_j of 30 to 60K) are calculated on the basis of these tests. The power cycling diagram shows the number of load cycles as a function of the junction temperature swing with the average temperature T_{jm} as a parameter. The given number of cycles represents a 1% failure probability.

Fig. 19 Power cycling lifetime as a function of ΔT_j and T_{jm} for IGBT4 modules



Cross-reference list

The cross-reference table gives an indication of a device replacement in three-phase inverter applications with medium switching frequencies (4…8kHz) and air cooling. The new IGBT 4 technology (~T4/E4) allows for a 25°C higher junction temperature compared with the former IGBT generations, which can be used for higher inverter currents. A smaller device might be feasible in terms of maximum junction temperature. The junction temperature is kept constant for IGBT3 (~126) and SPT (~128) to 125°C and for IGBT4 to 150°C.

The table is not applicable to all kinds of application and operating conditions. The maximum converter current is influenced by the different percentages of switching and conducting losses in the total losses, as well as by thermal resistances. These have been changed to different extents in the different IGBT generations. For a detailed analysis our online simulation tool SemiSel (http://semisel.semikron.com/) can be used. Alternatively, sales offices may be contacted for additional support.

Table 3 SEMITRANS cross-reference list

IGBT 3	SPT	IGBT 4		Case
	SKM 75GB128D	SKM 50GB12T4		2
	SKM 100GB128D	SKM 75GB12T4		2
SKM 195GB126D	SKM 145GB128D	SKM 100GB12T4		2
		SKM 150GB12T4		2
SKM 200GB126D	SKM 150GB128D	SKM 100GB12T4G		3
SKM 300GB126D	SKM 200GB128D	SKM 150GB12T4G		3
SKM 400GB126D	SKM 300GB128D	SKM 200GB12E4		3
SKM 600GB126D	SKM 400GB128D	SKM 300GB12E4		3
		SKM 400GB12E4		3
SKM 195GAL126D	SKM 145GAL128D	SKM 150GAL12T4*		2
SKM 200GAL126D		SKM 150GAL12T4*		3
SKM 400GAL126D	SKM 300GAL128D	SKM 200GAL12E4		3
SKM 600GAL126D	SKM 400GAL128D	SKM 300GAL12E4		3
		SKM 400GAL12E4		3
	SKM 145GAR128D	SKM 150GAR12T4*		2
	SKM 400GAR128D	SKM 300GAR12E4		3
		SKM 400GAR12E4		3
	SKM 300GA128D	SKM 300GA12E4*		4
SKM 600GA126D	SKM 400GA128D	SKM 300GA12E4		4
SKM 800GA126D	SKM 500GA128D	SKM 400GA12E4		4
		SKM 600GA12E4		4

* Modules with higher nominal chip rating

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Fig. 20 Example of maximum continuous inverter current $I_{out(rms)} = f(f_{sw})$
(V_{cc}=650V, V_{out}=400V, f_{out}=50Hz, T_a=40°C, air cooler $R_{th(s-a)}$=0.031K/W)

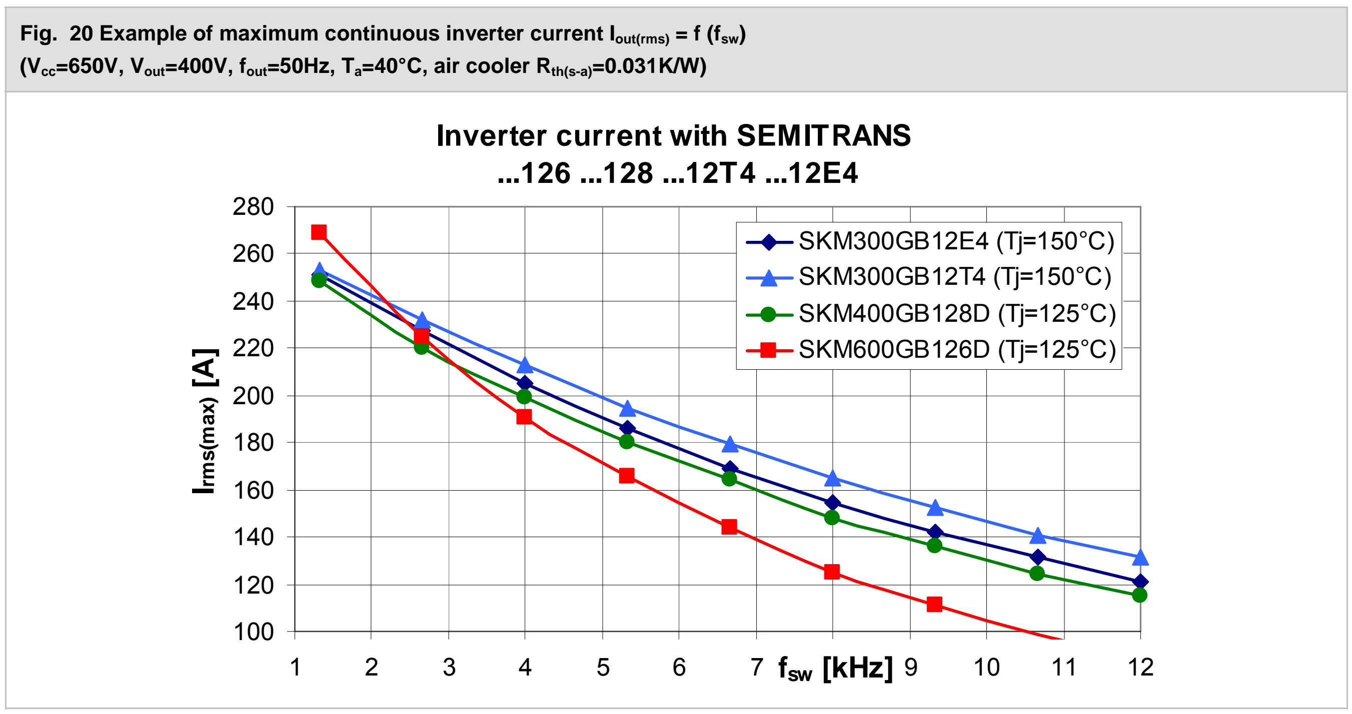
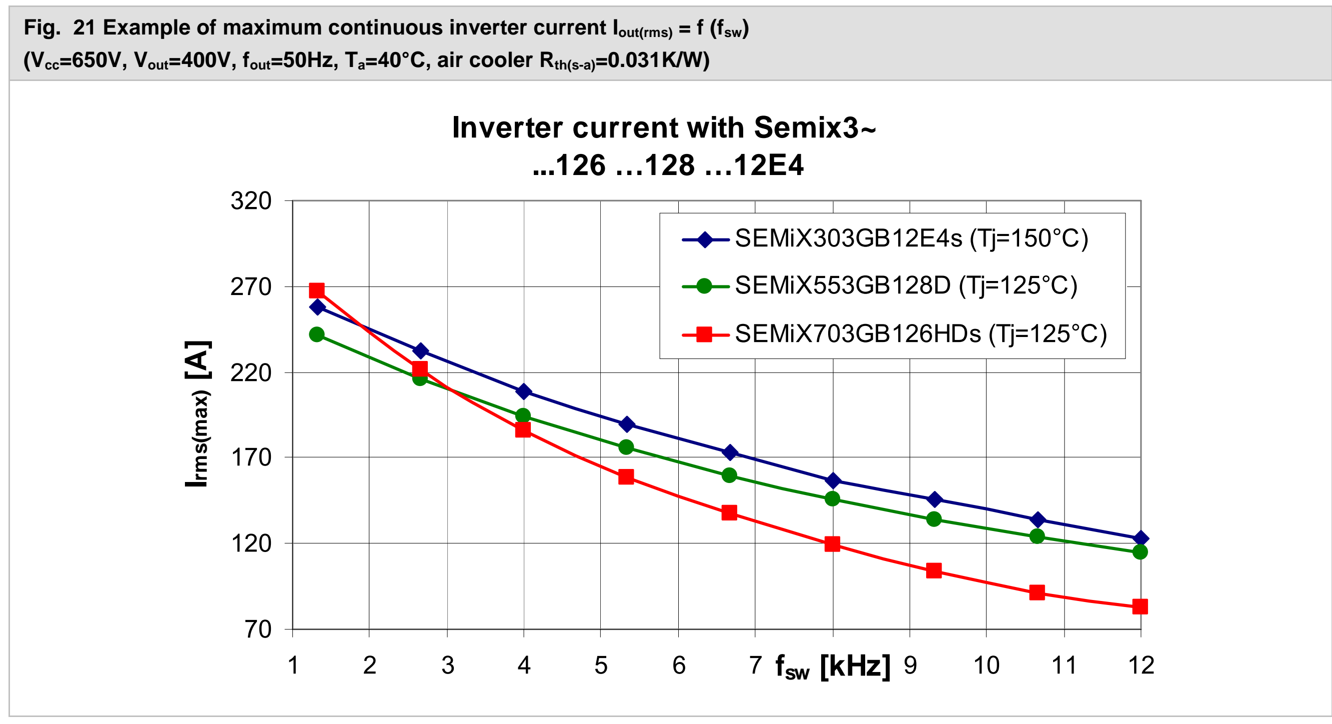


Table 4 SEMIX cross-reference list

Trench 3	SPT	Trench 4		Case
SEMiX 252GB126HDs	SEMiX 202GB128Ds	SEMiX 151GB12E4s*		2s
SEMiX 302GB126HDs	SEMiX 302GB128Ds	SEMiX 151GB12E4s		2s
SEMiX 452GB126HDs	SEMiX 352GB128Ds	SEMiX 202GB12E4s		2s
		SEMiX 302GB12E4s		2s
SEMiX 353GB126HDs				3s
SEMiX 503GB126HDs	SEMiX 403GB128Ds	SEMiX 303GB12E4s		3s
SEMiX 703GB126HDs	SEMiX 553GB128Ds	SEMiX 303GB12E4s		3s
SEMiX 604GB126HDs		SEMiX 453GB12E4s		3s
SEMiX 904GB126HDs	SEMiX 754GB128Ds	SEMiX 404GB12E4s		4s
		SEMiX 604GB12E4s		4s
SEMiX 101GD126HDs	SEMiX 101GD128Ds	SEMiX 71GD12E4s*		13
SEMiX 151GD126HDs	SEMiX 151GD128Ds	SEMiX 71GD12E4s		13
SEMiX 251GD126HDs	SEMiX 201GD128Ds	SEMiX 101GD12E4s		13
		SEMiX 151GD12E4s		13
SEMiX 353GD126HDc				33c
SEMiX 503GD126HDc	SEMiX 403GD128Dc	SEMiX 223GD12E4c		33c
SEMiX 703GD126HDc	SEMiX 553GD128Dc	SEMiX 303GD12E4c		33c
		SEMiX 453GD12E4c		33c
		SEMiX 151GAL12E4s		1s
SEMiX 452GAL126HDs	SEMiX 352GAL128Ds	SEMiX 302GAL12E4s*		2s
SEMiX 703GAL126HDs	SEMiX 553GAL128Ds	SEMiX 453GAL12E4s*		3s
		SEMiX 151GAR12E4s		1s
SEMiX 452GAR126HDs	SEMiX 352GAR128Ds	SEMiX 302GAR12E4s*		2s
SEMiX 703GAR126HDs	SEMiX 553GAR128Ds	SEMiX 453GAR12E4s*		3s

* Modules with higher nominal chip rating

Fig. 21 Example of maximum continuous inverter current $I_{out(rms)} = f(f_{sw})$ (V_{cc}=650V, V_{out}=400V, f_{out}=50Hz, T_a=40°C, air cooler $R_{th(s-a)}$=0.031K/W)



Symbols and terms used

Symbol	Term
CAL	Controlled axial lifetime diode
Cx	Auxiliary collector terminal
dv/dt	Rate of rise and fall of collector-emitter voltage
di/dt	Rate of rise and fall of collector current
E_{sw}	Switching energy
E_{on}	Turn-on switching energy
E_{off}	Turn-off switching energy
Ex	Auxiliary emitter terminal
f_{out}	Fundamental output frequency of an inverter circuit
f_{sw}	Switching frequency
IGBT	Insulated Gate Bipolar Transistor
I_{GM}	Peak gate current
I_C	Collector current
$I_{C(nom)}$	Nominal collector current of the device
I_{CM}	Peak collector current
L_{CE}	Internal parasitic inductance of a module
Q_G	Gate charge
R_G	Gate resistor
$R_{G(int)}$	IGBT module internal gate resistor
$R_{G(off)}$	Turn-off gate resistor
RT	Room temperature, about 25°C
$R_{th(s-a)}$	Thermal resistance between sink to ambient
$R_{th(j-c)}$	Thermal resistance between junction and case

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SPT	Soft punch through IGBT
T_a	Ambient temperature
TC	Temperature coefficient
Trench	Trench gate IGBT
$T_{j(max)}$	(Maximum) Junction temperature
T_{jm}	Medium junction temperature for power cycling with +/- 0,5*dT
$t_{d(on)}$	Turn-on delay time (10% V_{GE}→ 10% I_C)
$t_{d(off)}$	Turn-off delay time (90% V_{GE}→ 90% I_C)
t_f	Fall time of the collector current (90% I_C → 10% I_C)
t_r	Rise time of the collector current (10% I_C → 90% I_C)
V_{CC}	Collector-emitter supply voltage
V_{CE}	Collector-emitter voltage
$V_{CE(sat)}$	Collector-emitter saturation voltage
$V_{GE(off)}$	Turn-off gate voltage (output driver)
$V_{GE(on)}$	Turn-on gate voltage (output driver)
V_{GG}	Gate (driver) supply voltage
V_{out}	Output voltage of an inverter circuit

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